Renewable and Sustainable Energy Reviews 13 (2009) 2553–2561

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Power quality assessment of grid-connected wind farms considering regulations in turkey

Celal Kocatepe [a], Aslan İnan [a,*], Oktay Arıkan [a], Recep Yumurtacı [a], Bedri Kekezoğlu [a], Mustafa Baysal [a], Altuğ Bozkurt [a], Yener Akkaya [b]

[a] Yıldız Technical University, Department of Electrical Engineering, 34349 İstanbul, Turkey
[b] Turkish Electricity Transmission Company, R&D Manager, İnönü Bulvarı, 06490 Ankara, Turkey

ARTICLE INFO

Article history:
Received 5 March 2009
Accepted 12 June 2009

Keywords:
Wind power
Power quality
Harmonics
Flicker
Voltage unbalance

ABSTRACT

This paper presents measurement system and detailed analysis of power quality at the substation of two different wind farm sites which are of low and high power rate. Measurement system has been designed using a data acquisition board (DAQ), Labview software, Matlab programming and a portable PC. The system has been installed at medium voltage level at substation of both wind farms. The real measurement results at substations are compared to current regulations in Turkey.

Contents

1. Introduction

Increasing energy deficits and needs, with new technologies developing at the same time, has required to focus on alternative energy sources, mainly wind energy, beside conventional energy sources. Wind-powered electric generation is an ideal energy type because it is a pollution free, infinitely sustainable form of energy and does not produce greenhouse gasses or toxic waste.

The installation of wind plants (or farms) in utility grid has developed rapidly in last 20 years. As the wind power penetration into the grid increases, the power quality problems arising from wind farms become important area to be considered.

The integration of wind plants into the power system may cause power quality problems. Several wind turbine types have different power quality characteristics. The major power quality problems on grid-connected power plants are power variations, flicker and harmonics. Measurement of these disturbances is standardized by IEC 61000-4-30 which define the methods for measurement and interpretation of results for power quality parameters in 50/60 Hz a.c. power supply systems and IEC 61400-21 provides a uniform methodology to ensure consistency and accuracy in the testing and assessment of power quality characteristics of grid-connected wind turbines [1,2].

* Corresponding author. Tel.: +90 212 383 2442; fax: +90 212 259 4967.
E-mail address: inan@yildiz.edu.tr (A. İnan).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.06.014

Several investigations have been performed by the power quality measurements on wind farms in literature [3–5].

This paper presents the detailed results of long term (4 days) power quality measurements performed on two different wind plants which have different output-power level (10.2 MW and 30 MW). The study is conducted by real field measurements on the medium voltage (MV) level of the network to analyze the power quality characteristics of grid-connected wind plants.

2. Power quality measurement hardware and data acquisition

The general schematic and block diagram of the implemented power quality measurement system is given in Figs. 1 and 2, respectively. PQ measurements have been continuously carried out according to IEC 61000-4-30 during 4 days in the selected location [6]. The system consists of the following items: National Instruments DAQ Card 6036E, National Instruments SC-2040 S/H Card, 3 current probes (1 mV/10 mA), voltage divider cabling (100/3.8 V), Laptop computer, Labview software, Matlab software, uninterruptible power supply for current probes, and isolation transformer. The measurement hardware is placed in aluminum cases, in modified test vehicles, carrying the equipment and personnel to different measurement sites all over the country.

The measurement system has been installed in two different wind farms having wind turbines in the 600 kW and 1.5 MW named as Wind Farm-1 and Wind Farm-2, respectively. PQ measurements are continuously being carried out according to IEC 61000-4-30 during 4 days in these two substations (154/34.5 kV). Measurement results are evaluated in accordance with current regulations in Turkey [7,8].

3. Description of wind farms

Turkey has a very large potential for wind power, with a technical potential of 88,000 MW. In recent years, Turkey has taken important steps to expand its wind energy capacity. In 2008, the country has 30 wind energy power plants and, in May 2005, adopted a new renewable energy law to provide "feed-in tariffs" for electricity from renewable sources, primarily wind energy. Measurements made by the EIE (General Directorate of Electrical Power Resources) in Turkey over a number of years show that the average wind speed is 6.9 and 8.4 m/s at 50 m in Bandirma and Bozcaada, respectively [9].

Power quality measurements are performed in Wind Farm-1 and Wind Farm-2 in Turkey. Wind Farm-1 is in the distict of Bandirma (a district of Balikesir Province of Turkey) in The Marmara region and Wind Farm-2 is in the district of Bozcaada (a district of Canakkale Province of Turkey) in The Aegean Sea, as seen in Fig. 3.

Wind Farm-1 has installed capacity of 30 MW. Wind Farm-2 which is the third wind farm in Turkey has installed capacity of 10.2 MW and Table 1 shows summarized information of the wind farms in this study.

4. Measurement results and discussion

The power quality data from measurement are processed in accordance with IEC 61000-4-30/Class B, IEC 61000-4-7/Class B, IEC 61000-4-15/Class B, and IEEE 519-1992. This processing involves the computation of the power quality parameters, such as voltage and current harmonics, voltage flicker, voltage sags/swells, interruptions, and voltage unbalance. The recorded

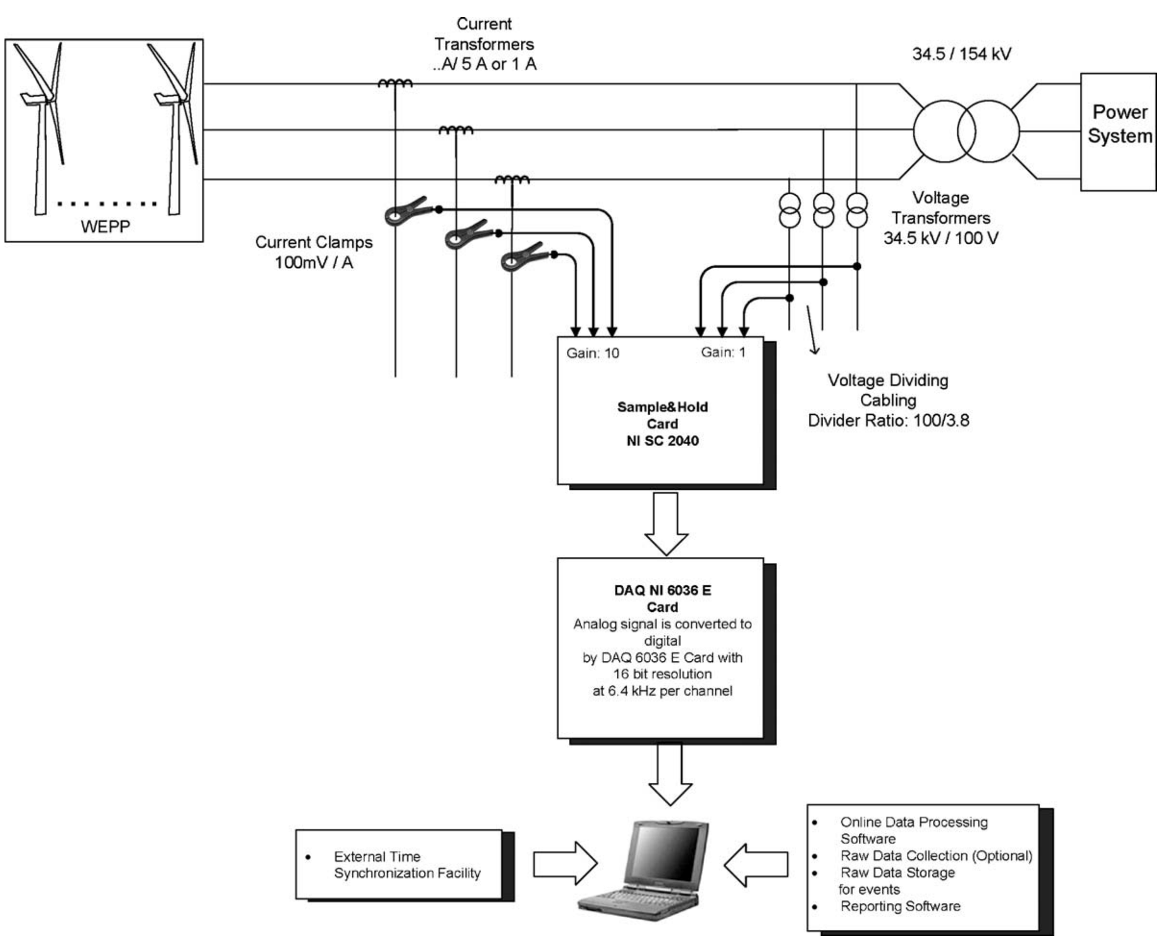

Fig. 1. Schematic diagram of power quality measurement system.

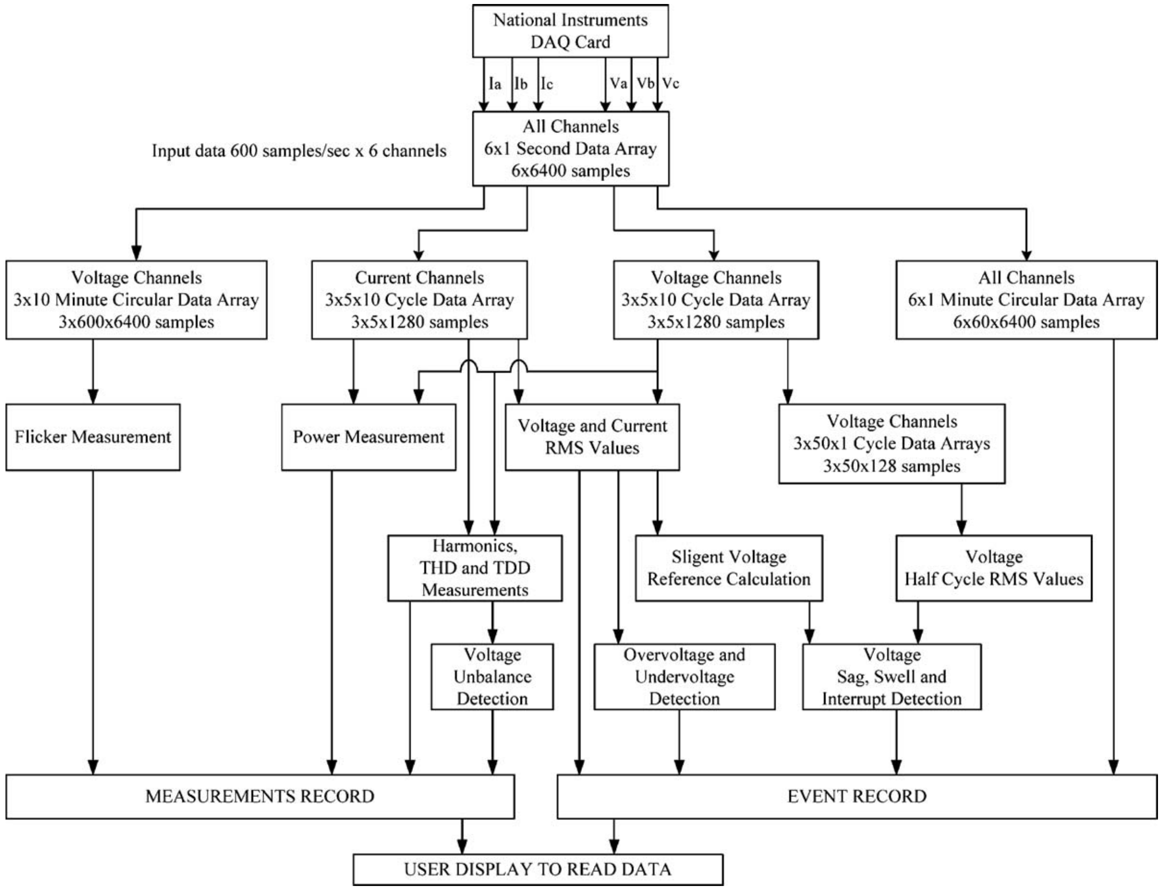

Fig. 2. Block diagram for analyzing of power quality measurements.

parameters are voltage and current rms values of all three phases for every 10 power frequency cycles, average values of current and voltage harmonics (up to 40th harmonics) every 3 s, active, reactive, and apparent power values and the power factor every second, and also the 10-min short-term (P_{st}) and 2-h long-term (P_{lt}) flicker values. The recorded data are grouped in two categories which are regularly recorded data and the event based data for power quality measurement evaluation.

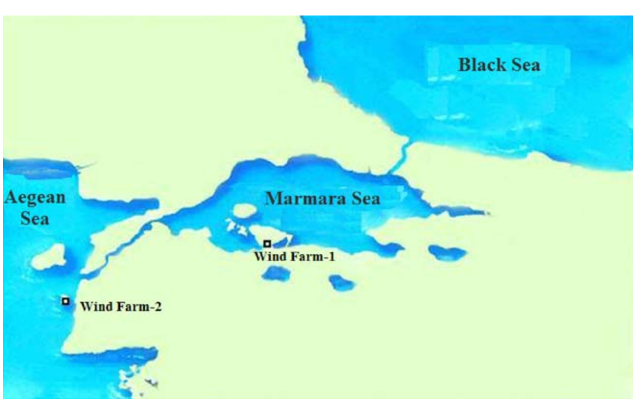

Fig. 3. Map of wind farms.

4.1. Voltage measurement

Voltage measurement is performed at medium voltage level of 34.5 kV in 34.5/154 kV substations. Medium voltage range in Turkey is 34.5 kV ±10%, i.e. upper voltage limit: 37.95 kV and lower voltage limit: 31.05 kV. As seen from true-rms voltage variation in 34.5 kV side in Fig. 4, voltage level does not exceed the limit through measurement period.

4.2. Active and reactive power measurement

Changes in wind speed often result in wind turbine active and reactive power fluctuations. The output real power changes with the wind speed on wind energy conversion system. As the real power increases, the voltage decreases. Fig. 5 shows active and passive power variations in Wind Farm-1 and Wind Farm-2.

4.3. Measurement of flicker

The most considerable effect of wind turbines is flicker problem. Output power of wind turbines has fluctuating character which causes power quality problems. Flicker is defined as periodic voltage drop or rise along 6–7 complete waves. Due to the inconstant output power in wind farms, flicker problem occurs.

Table 1
Generalized information about wind farms studied.

Name	Location	Date taken under operation	Installed capacity	Turbine capacity
Wind Farm-1	Bandirma, Balikesir	2006	30 MW	20 × 1.5 MW
Wind Farm-2	Bozcaada, Canakkale	2000	10.2 MW	17 × 600 kW

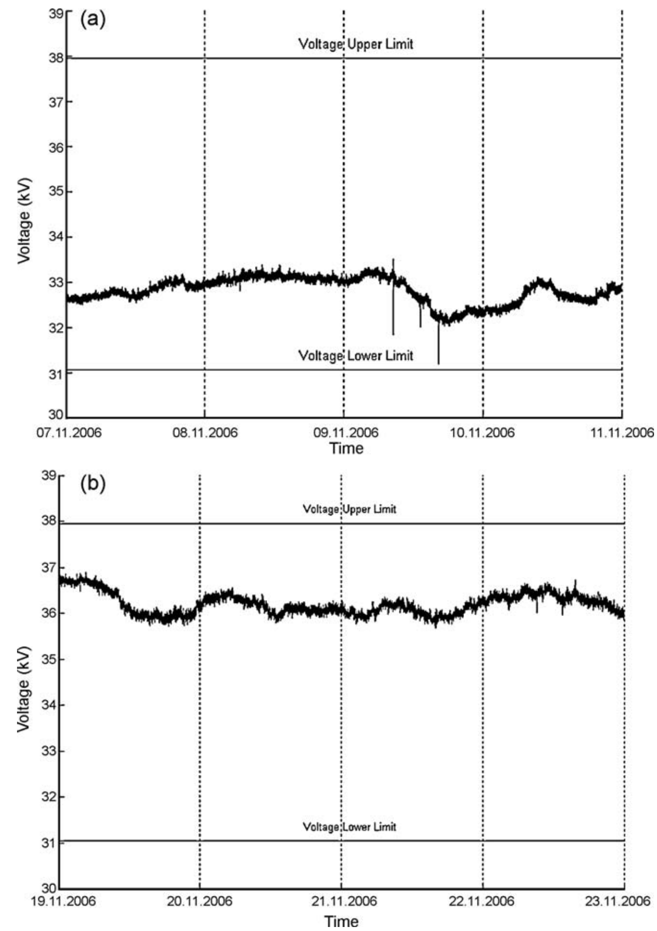

Fig. 4. Voltage variation: (a) Wind Farm-1 and (b) Wind Farm-2.

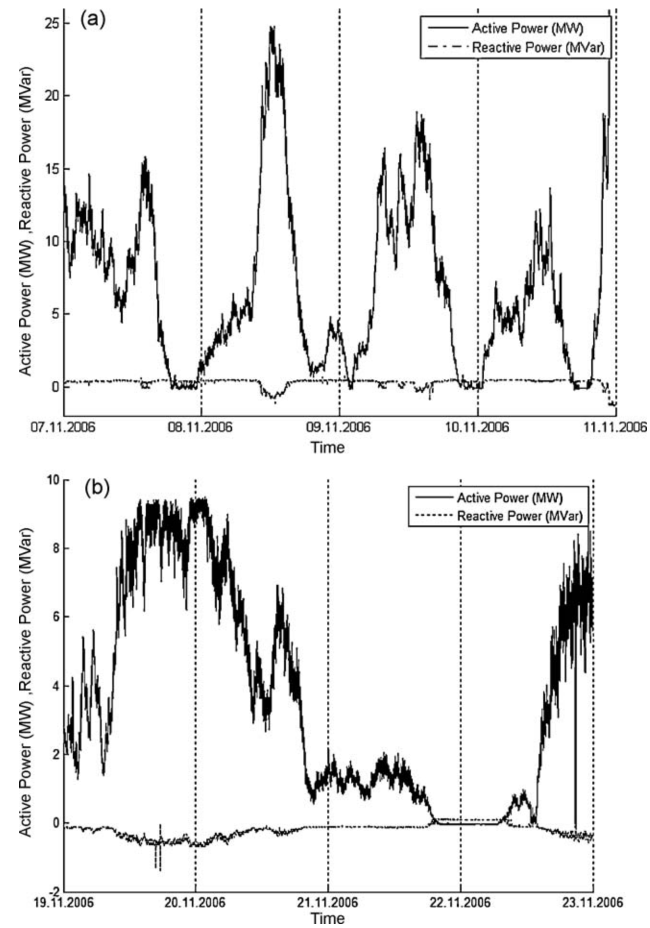

Fig. 5. Active and reactive power variation: (a) Wind Farm-1 and (b) Wind Farm-2.

As seen in Figs. 6–9, P_{st} and P_{lt} values occasionally exceed the limits defined in the Electricity Market Grid Regulation in Table 2 through measurement period at 34.5 kV side.

By comparing measurement period to time interval in which the standard values are exceeded for all three phases, percentage values of measurement interval exceed the limits are given in Table 3 for Wind Farm-1 and Table 4 for Wind Farm-2.

These values are evaluated according to section of IEC 61000-4-30 named flicker in which it is recommended that a probability weekly values 99% for P_{st} or probability weekly values 95% for P_{lt} might be compared to standard values.

As will be seen from Table 3, for Wind Farm-1, short-term flicker severity values P_{st} satisfy the condition that measurement values might exceed the limits in 1% of measurement period for A and B phases except for C phase. Similarly, long-term flicker severity values P_{lt} satisfy the condition that measurement values might be exceed the limits in 5% of measurement interval for A and B phases except for C phase.

Table 2
Acceptable maximum flicker severity limits for 34.5–154 kV power transmission systems in compliance with Electricity Transmission System Supply Reliability and Quality Regulation in Turkey.

Voltage level at PCC	Flicker severity			
	A_{st}	P_{st}	A_{lt}	P_{lt}
154 kV and above	0.61	0.85	0.25	0.63
34.5 kV through 154 kV	0.91	0.97	0.37	0.72
1 kV through 34.5 kV	1.52	1.15	0.61	0.85
1 kV and below	1.52	1.15	0.61	0.85

Table 3
P_{st} and P_{lt} values for Wind Farm-1.

Phase A	Percentage value of 10-min averages (P_{st}) that exceed the limits	0.679348
Phase B	Percentage value of 10-min averages (P_{st}) that exceed the limits	0.543478
Phase C	Percentage value of 10-min averages (P_{st}) that exceed the limits	1.08696
Phase A	Percentage value of 2-h averages (P_{lt}) that exceed the limits	2.40964
Phase B	Percentage value of 2-h averages (P_{lt}) that exceed the limits	3.61446
Phase C	Percentage value of 2-h averages (P_{lt}) that exceed the limits	9.63855

Table 4
P_{st} and P_{lt} values for Wind Farm-2.

Phase A	Percentage value of 10-min averages (P_{st}) that exceed the limits	0.78125
Phase B	Percentage value of 10-min averages (P_{st}) that exceed the limits	0.78125
Phase C	Percentage value of 10-min averages (P_{st}) that exceed the limits	0.78125
Phase A	Percentage value of 2-h averages (P_{lt}) that exceed the limits	4.81928
Phase B	Percentage value of 2-h averages (P_{lt}) that exceed the limits	4.81928
Phase C	Percentage value of 2-h averages (P_{lt}) that exceed the limits	4.81928

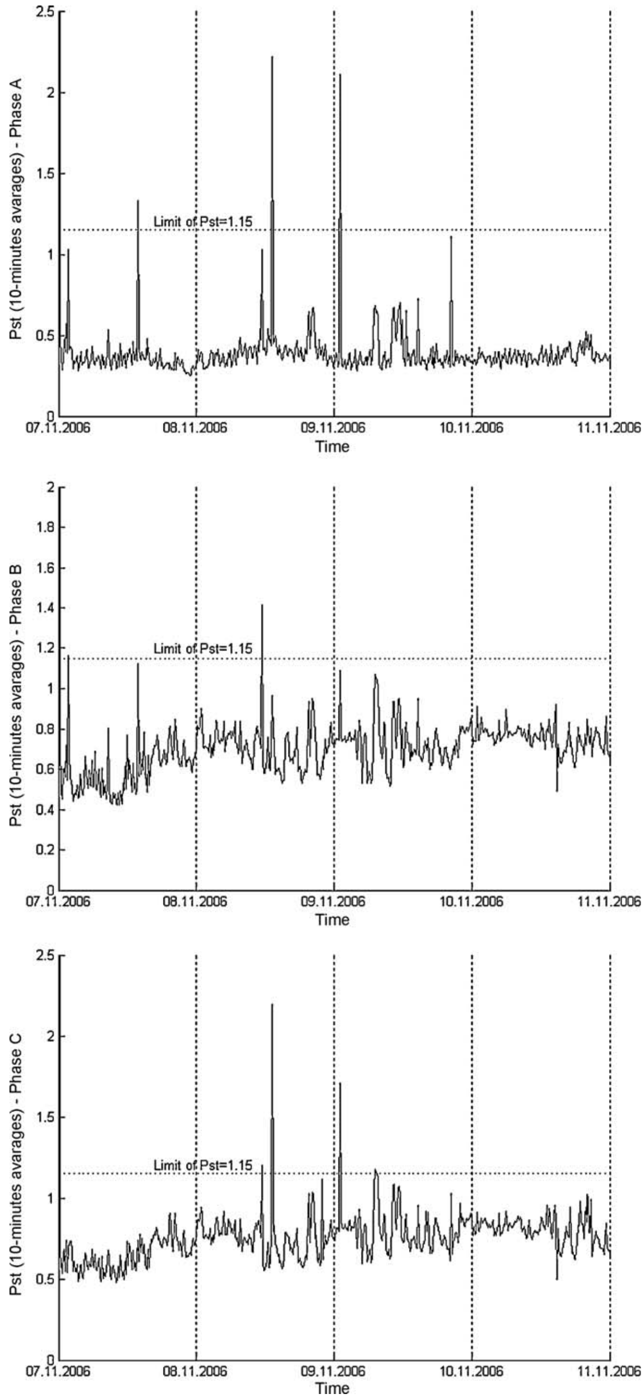

Fig. 6. Short-term flicker variations in phases A–C for Wind Farm-1.

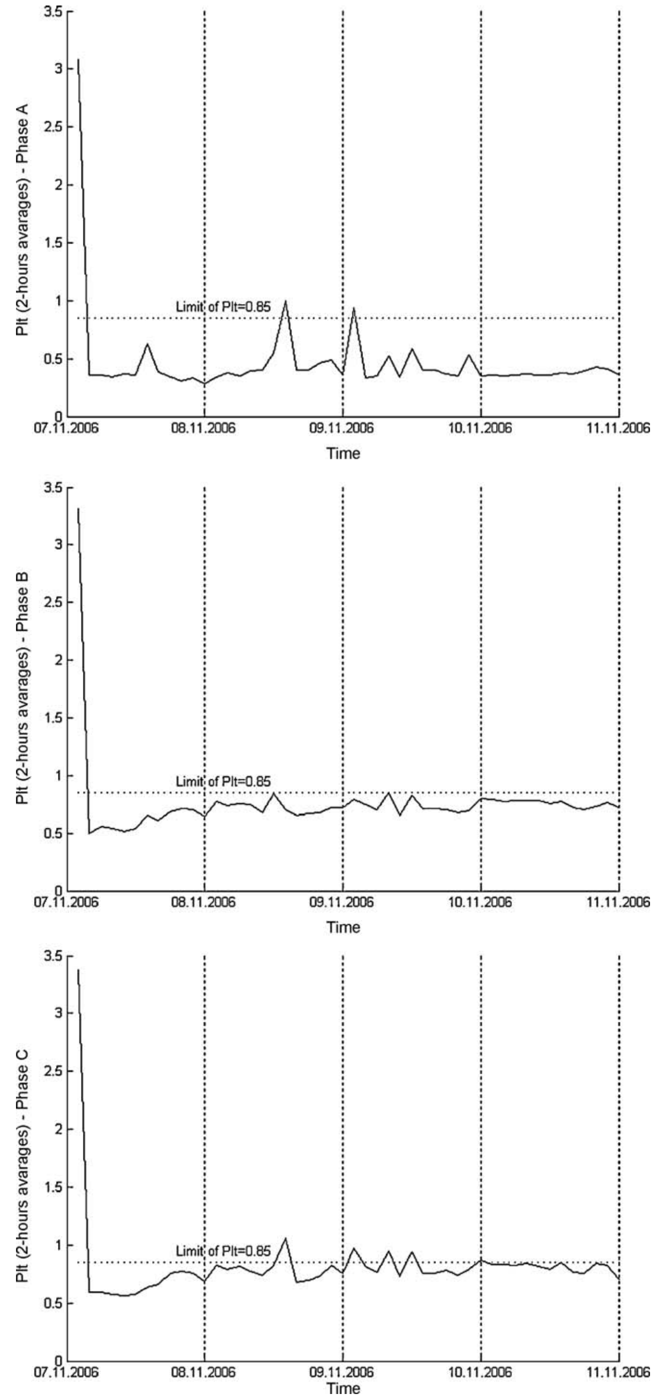

Fig. 7. Long-term flicker variations in phases A–C for Wind Farm-1.

Table 5
Acceptable harmonic voltage limits for 20–154 kV power transmission systems in compliance with Electricity Market Grid Regulation in Turkey.

Odd harmonics (non-triplen)		Odd harmonics (triplen)		Even harmonics	
Harmonic order	Harmonic voltage (%)	Harmonic order	Harmonic voltage (%)	Harmonic order	Harmonic voltage (%)
5	1.5	3	1.5	2	1.0
7	1.5	9	0.75	4	0.8
11	1.0	15	0.3	6	0.5
13	1.0	21	0.2	8	0.4
17	0.75	>21	0.2	10	0.4
19	0.75			12	0.2
23	0.5			>12	0.2
25	0.5				
>25	0.2 + 0.3 (25/h)				

Total harmonic distortion limit, 3%.

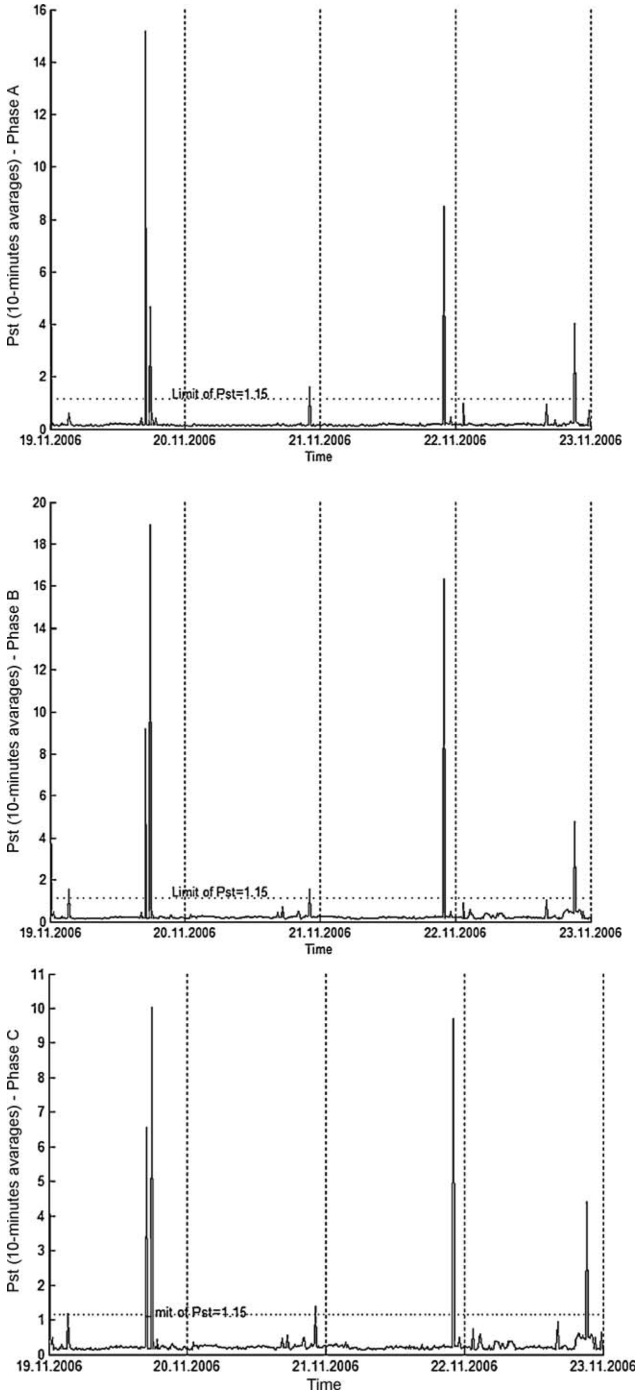

Fig. 8. Short-term flicker variations in phases A–C for Wind Farm-2.

As will be seen from Table 4, for Wind Farm-2, short-term flicker severity values P_{st} satisfy the condition that measurement values might exceed the limits in 1% of measurement period for all three phases. Similarly, long-term flicker severity values P_{lt} satisfy the condition that measurement values might be exceed the limits in 5% of measurement interval for all phases. It can be concluded that flicker values meet the standard values.

4.4. Measurement of harmonics

Voltage and current harmonics are evaluated as 1-s averages. Acceptable voltage harmonic limits in the Electricity Market Grid Regulation and acceptable current harmonic limits in the Electricity Transmission System Supply Reliability and Quality Regulation in Turkey are given in Tables 5 and 6, respectively.

As seen from Figs. 10(a) and 11(a), in evaluation of voltage harmonics, THD_v for Wind Farm-1 exceed the limits defined in Electricity Market Grid Regulation in Table 5 but not exceed for Wind Farm-2.

In addition, from the point of view of individual voltage harmonics, as seen from Figs. 12(a) and 13(a), only 5th voltage

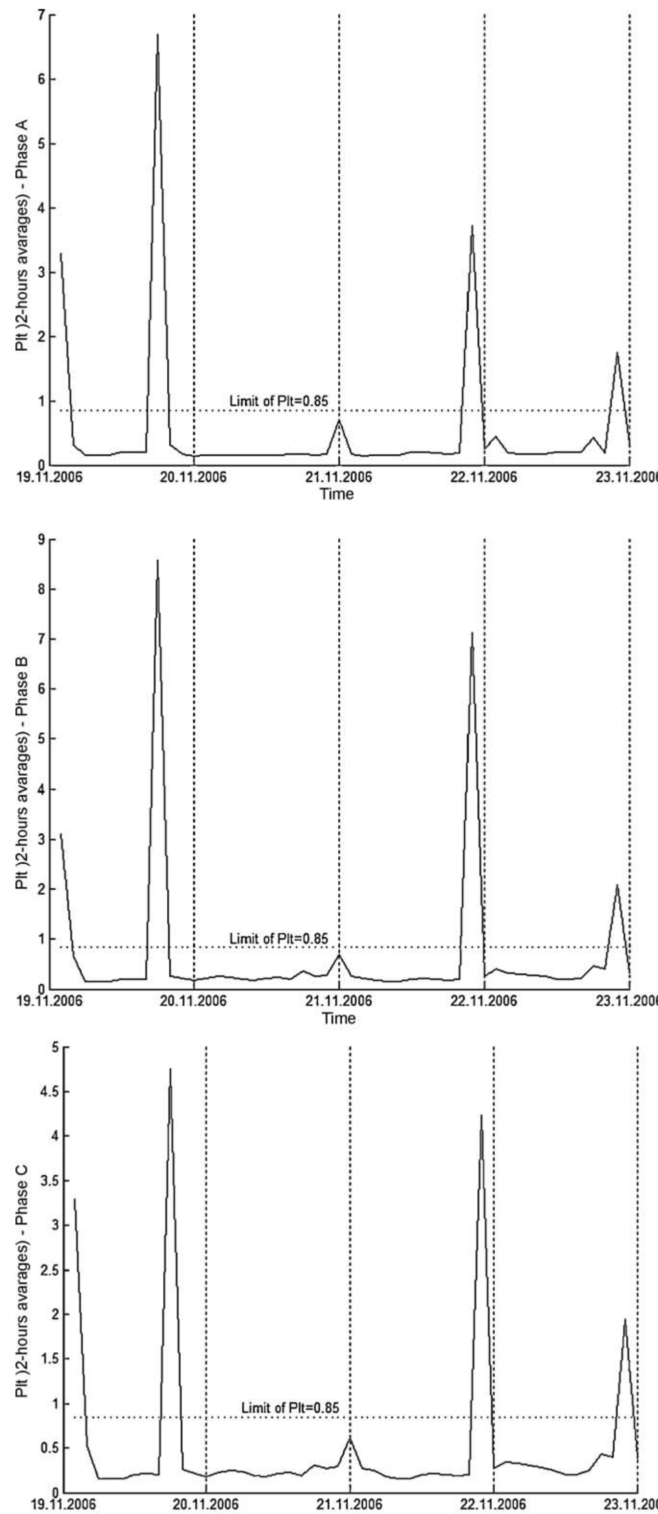

Fig. 9. Long-term flicker variations in phases A–C for Wind Farm-2.

Table 6
Acceptable harmonic current limits in compliance with Electricity Transmission System Supply Reliability and Quality Regulation in Turkey.

Harmonic order (odd harmonics)		MV 1–34.5 kV				
		I_{sc}/I_L				
Group	No.	<20	20–50	50–100	100–1000	>1000
Odd harmonics	3	4	7	10	12	15
	5	4	7	10	12	15
	7	4	7	10	12	15
	9	4	7	10	12	15
	11	2	3.5	4.5	5.5	7
	13	2	3.5	4.5	5.5	7
	15	2	3.5	4.5	5.5	7
	17	1.5	2.5	4	5	6
	19	1.5	2.5	4	5	6
	21	1.5	2.5	4	5	6
	23	0.6	1	1.5	2	2.5
	25	0.6	1	1.5	2	2.5
	27	0.6	1	1.5	2	2.5
	29	0.6	1	1.5	2	2.5
	31	0.6	1	1.5	2	2.5
	33	0.6	1	1.5	2	2.5
	$h > 33$	0.3	0.5	0.7	1	1.4
Total demand distortion	5	8	12	15	20	

harmonic component for Wind Farm-2 exceeds the limit value. Other individual voltage harmonics components in Wind Farm-1 and Wind Farm-2 are in under the limit values specified in Table 5.

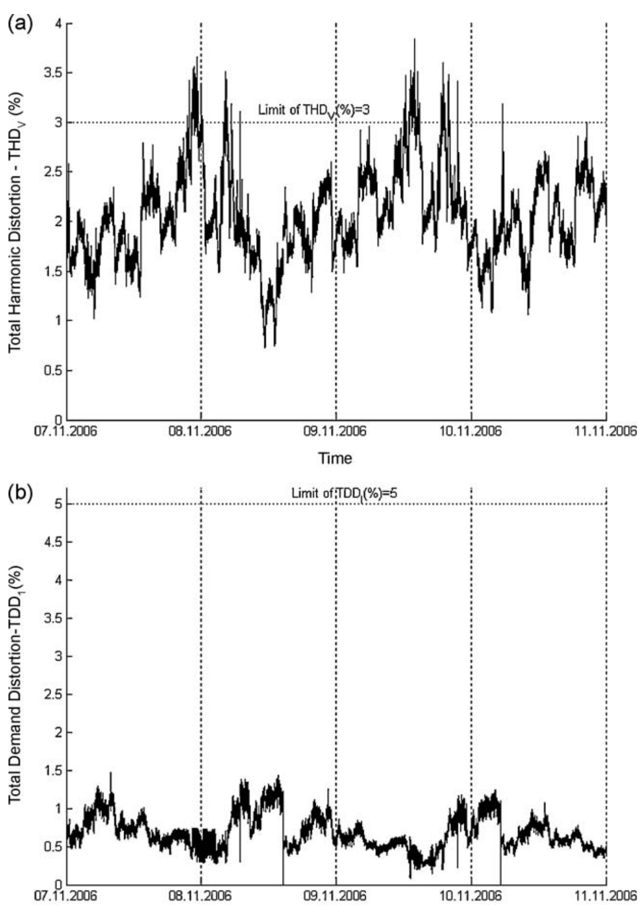

Fig. 10. (a) Total harmonic distortion and (b) total demand distortion for Wind Farm-1.

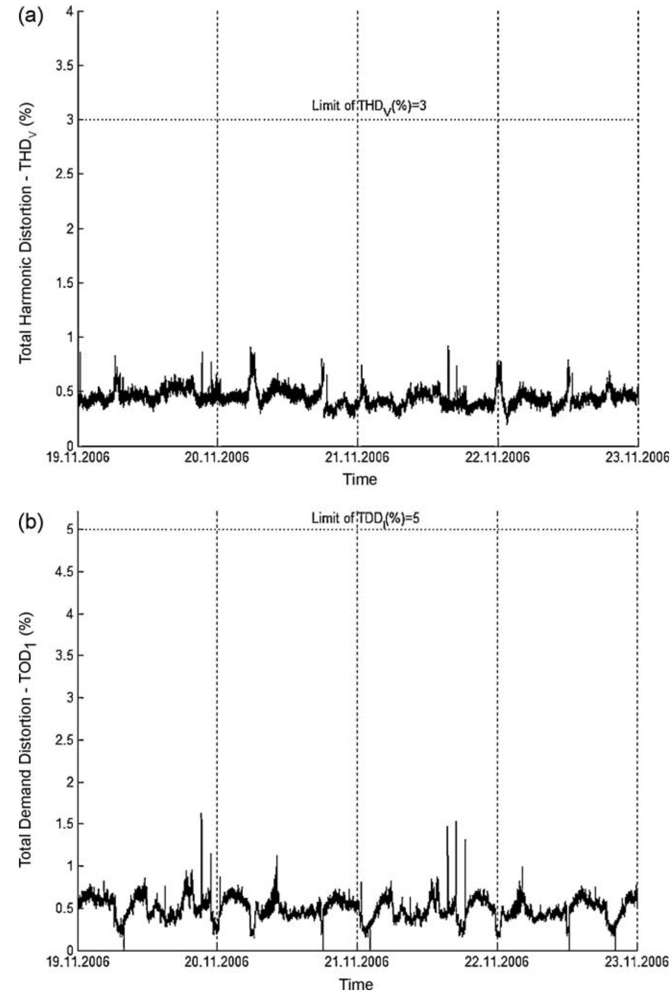

Fig. 11. (a) Total harmonic distortion and (b) total demand distortion for Wind Farm-2.

For Wind Farm-2, calculated maximum short-circuit current (I_{sc}) is 2002 A. The measured maximum demand load current (I_L) is 158 A. Ratio of I_{sc}/I_L is calculated as 2002/158 = 12.67 for voltage level of 34.5 kV. For Wind Farm-1, I_{sc} = 5324 A, I_L = 536.8 A and ratio of I_{sc}/I_L is calculated as 5324/536.8 = 9.9 for voltage level of 34.5 kV.

According to ratio of I_{sc}/I_L, standard limits are specified from acceptable current harmonic limits defined by Electricity Transmission System Supply Reliability and Quality Regulation in Turkey. By comparing limit values in Table 6 to measured values, limit of total demand distortion is not exceeded in both Wind Farm-1 and Wind Farm-2 as shown in Figs 10(b) and 11(b).

As for individual current harmonics in Wind Farm-1 and Wind Farm-2, as seen from Figs. 12(b) and 13(b), are in under the limit values specified in Table 6.

4.5. Power quality events

Power quality event detection comprises momentary voltage sag, momentary voltage swell, momentary voltage unbalance and voltage interruption. In order to determine power quality events, real data was collected at a rate of 3200 samples/s/channel using non-overlapping windows of 1 s length. The event mechanism is triggered, whenever one of the voltage sag, swell, interruption or unbalance is exceeding a certain threshold. In case of an event, raw data consisting of 1 s neighborhood of the exact event time are recorded.

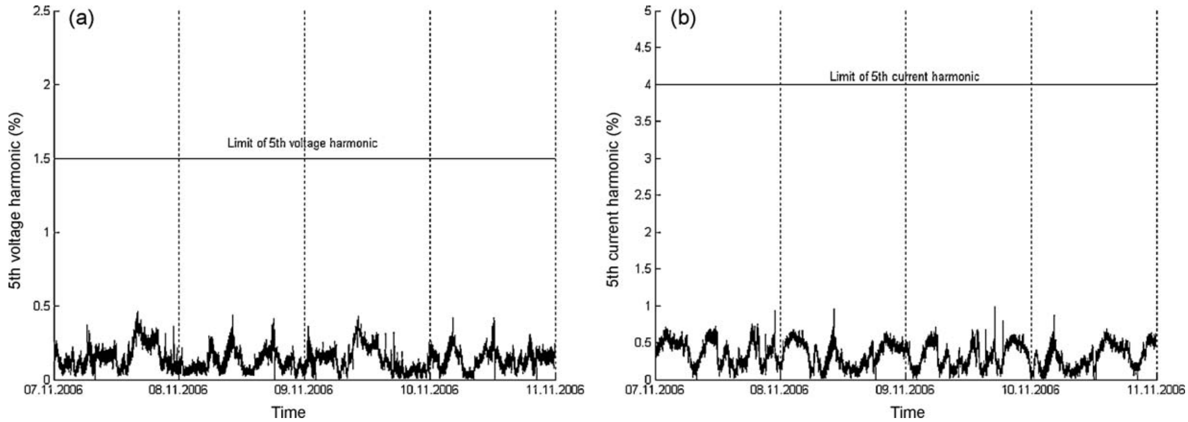

Fig. 12. (a) 5th voltage harmonic and (b) 5th current harmonic component for Wind Farm-1.

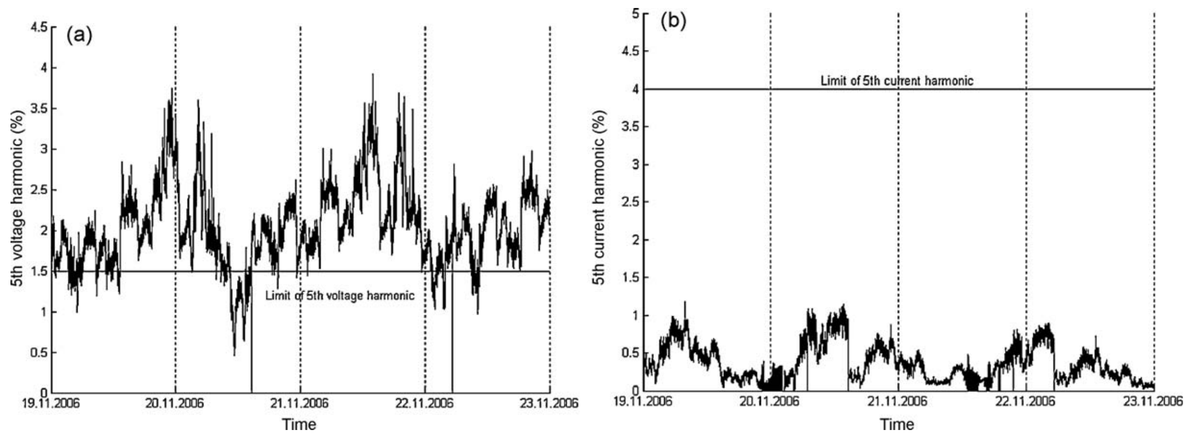

Fig. 13. (a) 5th voltage harmonic and (b) 5th current harmonic component for Wind Farm-2.

Table 7
The list of power quality events in the voltage.

Wind farm	Number of event	Number of voltage swell	Number of voltage sag	Number of voltage unbalance
Wind Farm-1	9	3	0	6
Wind Farm-2	13	4	3	6

The voltage sag is defined as a short duration reductions in the rms supply voltage that can last a few milliseconds to a few cycles, on the other hand the voltage swell is defined as a short duration increasing in rms supply voltage.

Voltage unbalance is the non-equality of voltage magnitudes and/or voltage angles among three-phase system and is regarded as a power quality problem. Voltage unbalance can be caused by the unequal distribution of single-phase loads, unsymmetrical transformer windings and transmission impedance, adjustable speed drives operations and many other causes.

Total event number for measurement period in Wind Farm-1 and Wind Farm-2 is given in Table 7. According to definitions in the IEC 61000-4-30, thirteen events in Wind Farm-2 and nine events in Wind Farm-1 in terms of voltage swell, voltage sag and voltage unbalance were observed. During in this measurement period, no voltage interruption was coincided in both wind farms.

5. Conclusions

In this paper, the power quality issues of two wind plants at the point of common coupling with the HV transmission network are investigated. Flicker, harmonics, and power quality events (voltage sag, swell, unbalance) have been analyzed and evaluated based on current regulations in Turkey.

The investigation shows that the wind plants have a slightly negative impact on the medium level of transmission network. This analysis on real measurements is performed on only two wind farms. In order to exactly simulate of grid-connected wind farms, performing many real measurements will be necessary.

Acknowledgements

Authors would like to thank the Public Research Support Group (KAMAG) of the Scientific and Technological Research Council of Turkey (TUBITAK) for full financial support of the project namely the National Power Quality Project of Turkey, Project No.: 105G129.

References

[1] IEC 61000-4-30. Electromagnetic compatibility (EMC)—Part 4: testing and measurement techniques. Power quality measurement methods.
[2] IEC61400-21. Wind turbine generator systems—Part 21: measurement and assessment of power quality characteristics of grid connected wind turbines.
[3] Emilio Ghiani, Fabrizio Pilo, Gian Giuseppe Soma, Gianni Celi. Power quality measurements performed on a large wind park at low and medium voltage level. In: The International Conference on Power Systems Transients (IPST'07); 2007.
[4] Santjer F, Gerdes GJ, Klosse R. Power quality measurements at wind turbines. In: Power Quality Proceedings; 1997. p. 283–92.
[5] Torbjörn Thiringer. Power quality measurements performed on a low-voltage grid equipped with two wind turbines. IEEE Trans Energy Conv 1996;11: 601–6.

[6] Özdemirci E, Akkaya Y, Boyrazoğlu B, Buhan S, et al. In: Mobile monitoring system to take PQ snapshots of turkish electricity transmission system IMTC 2007; 2007.
[7] Electricity Market Grid Regulation by The Electricity Market Regulatory Authority for Turkey. <http://www.epdk.gov.tr>.
[8] Electricity Transmission System Supply Reliability and Quality Regulation by The Electricity Market Regulatory Authority for Turkey. <http://www.epdk.gov.tr>.
[9] Kamil Kaygusuz, Ahmet Sarı. Renewable energy potential and utilization in Turkey. Energy Conv Manage 2003;44:459–78.